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In a recent experimental study [1] of the reaction ^{17}F$(p,2p)^{16}$O two-proton events were measured from excitations near a 1^-, $E^*=6.15$ MeV state in ^{18}Ne. We calculate by means of R-matrix theory the resonant two-proton production cross section and branching ratios. We conclude that it is unlikely that two-proton production via population of the 1^- state is sufficient to explain the observed two-proton events. Alternative sources of such events are discussed.

Introduction. In recent paper [1], states in ^{18}Ne were populated in the ^{17}F+p reaction. High quality results for the one-proton excitation function are obtained in the energy range 0.4–2.45 MeV, and the question arises whether exotic two-proton emission processes can be seen in such an experiment. Because there are no intermediate states in ^{17}F available for sequential decay, the region of the ^{18}Ne spectrum below 6.5 MeV might be envisaged as a good place to study simultaneous two proton decay. This needs a theory of two proton decays.

We therefore review the theoretical foundations of the two mechanisms (as mentioned in the introduction of paper [1]): (i) diproton mechanism [2] and (ii) democratic decay [5]. In his often-referenced paper [2], Goldansky pointed that a curious quantum mechanical effect is possible in some proton-rich nuclei: what he calls "true two-proton emission" takes place if there are *no two-body decay channels at all* due to energy conditions in the subsystems. The fingerprint of this effect should be "the energy correlation between the protons during the two-proton decay, which leads to their energies being almost equal". Goldansky also noticed that the estimated penetrability for two s-wave protons is very close to the penetrability for the 'diproton' (charge 2 'particle' with zero energy of internal motion). We remark that this similarity of penetrabilities has led to the widespread idea that Goldansky expected two-proton decay to produce two protons with almost coincident *velocities*, whereas he predicted merely coincident *energies*.

A slightly different view on the phenomenon is provided by the concept of democratic decay [3–5]: it was shown experimentally for decay of the ^{6}Be g.s. that the energy distribution between the protons is broad ('democratic') and no 'diproton'-type correlation was observed. It was suggested that the reason for the broad distributions is the absence of narrow states in all subsystems in this decay. This is less stringent condition than the condition for 'true two-proton decay' in the paper of Goldansky, namely that the "positive binding energy of the first proton must be larger than the half width of the emission of the second one". However, the qualitative prediction of Goldansky that protons should evenly share the energy was confirmed in these studies. It was shown in [4] that the energy distributions in democratic decays can be described by the expression

$$dN/d\epsilon \propto \sqrt{\epsilon(E_{2p}-\epsilon)}\;|A|^2 \qquad (1)$$

where ϵ is relative energy of the protons, E_{2p} is the energy of the resonance relative to the $2p$ threshold, and amplitude A depends only weakly on ϵ.

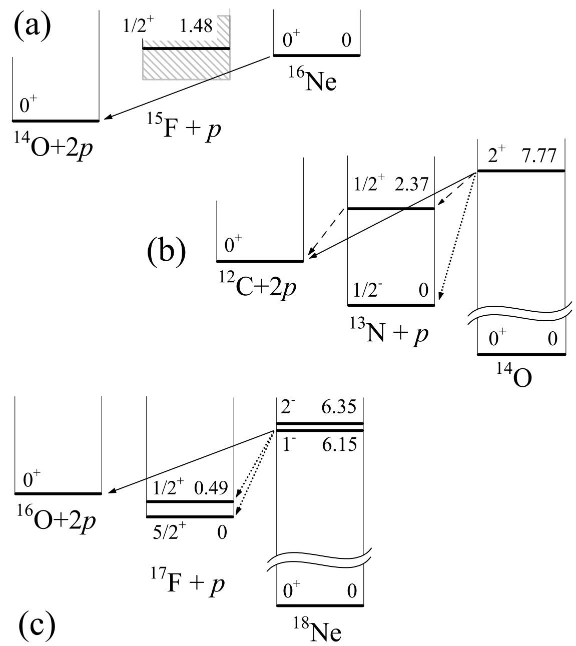

FIG. 1. Schemes of different two-proton decays illustrating (a) true two-proton decay, (b) sequential decay, and (c) simultaneous emission of two protons, but with two-body ^{17}F + p channel dominating.

More detailed insight into the different decay modes can be found in the paper [6], where the applicability of simple models of two-proton decay is carefully discussed. What is important here is that the reaction studied in the experiment of [1] is neither exactly within the scope of the original idea of Goldansky [2] for two-proton radioactivity, nor exactly within the scope of idea of democratic decay [3–5]. This implies that other breakup mechanisms could also be important, and we now review such possibilities.

Qualitatively different cases of two-proton emission are illustrated in Fig. 1. Presumably democratic two-proton decay of the ^{16}Ne ground state (Fig. 1a, [7–9]), where there are no strongly correlated subsystems, is compared with decays of excited states in ^{14}O (Fig. 1b, [10]) and ^{18}Ne (Fig. 1c, [1]), where binary decay channels are opened. The conceptual difference between the experiments Refs. [10] and [1] is that there is a sequential decay branch through the $1/2^+$ state at 2.37 MeV in ^{13}N (Fig. 1b), which was shown to be important decay mode in [10]. In the case of ^{18}Ne sequential decay is not possible, but one-proton decay is still allowed to the weakly bound states in ^{17}F ($5/2^+$ ground state, $E_b = 0.6$ MeV and $1/2^+$, $E_b = 0.11$ MeV, Fig. 1c). In the recent experiment [1] the flux in the ^{17}F+p channel is orders of magnitude larger than in the three-body ^{16}O+p+p channel and can not be neglected in the study of the $2p$ channel. In such a case it will be very difficult to disentangle the three-body decay of ^{18}Ne states from the breakup of ^{17}F on a proton target (which also provides two protons in the final state), making the interpretation of the reaction more complicated.

We therefore examine the nature of the reaction [1] by means of R-matrix theory, to see whether the observed two-proton events can be explained in terms of three-body decay from the 1^-, $E^* = 6.15$ MeV resonance state in ^{18}Ne. We calculate the two-proton production cross section and branching ratios.

Estimates. To estimate the cross section value for two-proton production via the resonance compound state with definite J^π we use the standard formula (Ref. [14])

$$\sigma^J_{\alpha\beta}(E) = \frac{\pi}{k^2}\,\frac{\Gamma_\alpha \Gamma_\beta}{(E_R - E)^2 + \Gamma^2/4}\,\frac{2J+1}{(2J_{1\alpha}+1)(2J_{2\alpha}+1)}\,, \quad (2)$$

where α and β label the entrance and exit channels, $J_{1\alpha}$ and $J_{2\alpha}$ are the spins of the particles in the entrance channel, Γ is the total (experimental) width of the resonance and Γ_i are partial widths. For the 1^- state $\Gamma = 50$ keV [1]. To obtain the complete cross section in the case of elastic scattering ($\alpha = \beta$) the Coulomb and potential scattering together with any interference terms must be added to Eq. (2).

The resonant $2p$ production cross section via a 1^- state is

$$\sigma^{1^-}_{2p}(E_R) = \frac{\pi}{k^2}\,\frac{\Gamma_{1p}(\mathrm{gs})}{\Gamma}\,\frac{\Gamma_{2p}}{\Gamma}\,, \quad (3)$$

where, evaluated on the resonance, $\pi/k^2 = 0.31$ barn, and $\Gamma_{1p}(\mathrm{gs})$ is the decay width to the ^{17}F ground state. It can be seen from (3) that cross section value of 310 mb is the upper limit for resonance processes via the 1^- state of ^{18}Ne at 6.15 MeV.

If the decay of the 1^- state to the excited $1/2^+$ state in ^{17}F is negligible, the ratio $\Gamma_{1p}(\mathrm{gs})/\Gamma$ is very close to unity. A more realistic estimate takes into account the variation of penetrabilities with decay energy. The conventional R-matrix formula is [15]

$$\Gamma^i_{1p}(E) = 2\,S^i_{1p}\,\frac{3}{2M^1_{17} r_c^2}\,P_l(E, r_c, Z(^{17}\mathrm{F}))\,, \quad (4)$$

where M^j_k is the reduced mass for particles with mass numbers j and k. In this article the channel radius r_c is varied from 2.5 to 4.5 fm to give an idea of the theoretical uncertainties associated with this parameter. Neglecting the difference of spectroscopic factors S^i_{1p} for the ^{17}F(gs)+p and ^{17}F($1/2^+$)+p channels we obtain $\Gamma_{1p}(\mathrm{gs})/\Gamma_{1p}(1/2^+) \sim 2$, and hence $\Gamma_{1p}(\mathrm{gs})/\Gamma \sim 2/3$. If the inelastic channel ^{17}F($1/2^+$)+p has a large spectroscopic factor, it can influence drastically the cross section of the two-proton decay. This is connected with the fact that the large spectroscopic factor $S^{1/2+}_{1p}$ will decrease the ratio $\Gamma_{1p}(\mathrm{gs})/\Gamma$ in Eq. (3) and will lead to smaller $2p$ production through the 1^- resonance. Unfortunately there was no experimental identification of the inelastic ^{17}F($1/2^+$)+p channel in [1]. Such identification is highly desirable to provide more reliable estimates for the process.

To estimate the *simultaneous* two-proton emission width we use a formula from [6] (similar to one given in [2]):

$$\Gamma_{2p}(E_{2p}) = 2\,S_{2p}\,\frac{3}{\pi r_c^3 (M^1_{16})^{3/2} E^{1/2}_{2p}} \int_0^1 dx$$
$$\times P_{l_1}\left(xE_{2p}, r_c, Z(^{16}\mathrm{O})\right) P_{l_2}\left((1-x)E_{2p}, r_c, Z(^{16}\mathrm{O})\right)\,, \quad (5)$$

where l_1 and l_2 are the angular momenta of the 2 protons, and E_{2p} is the three-body energy relative to the two-proton breakup threshold. The coefficient in front of the penetrabilities plays the role of a reduced width and is normalized in the spirit of the Wigner limit: without any barriers the width is the average inverse flight time for the distance $r_c/3$. We certainly expect the two-proton spectroscopic factor to be smaller than the one-proton spectroscopic factor: $S_{2p} < S_{1p}$. However, assuming $S_{2p} = S_{1p}$ the upper limit for the estimated branching ratio with $l_1 = 0$ and $l_2 = 1$ is $\Gamma_{2p}/\Gamma = (1.5-5) \times 10^{-4}$ (for r_c in the range 2.5–4.5 fm, see solid curve in Fig. 2).

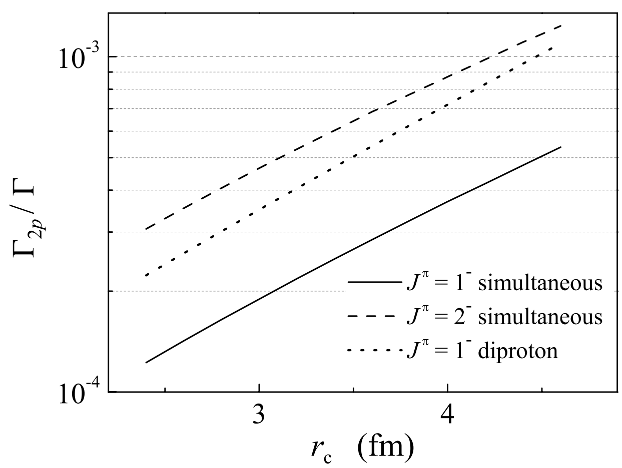

FIG. 2. The ratio Γ_{2p}/Γ as function of channel radius r_c estimates in two-proton and 'diproton' models. Solid and dashed curves correspond to 1^- state (simultaneous and 'diproton' emission) and dotted curve corresponds to 2^- state (simultaneous emission only).

Another simple estimate of the branching ratio is provided by the *diproton* model:

$$\Gamma_{2p}(E_{2p}) = 2\,S_{2p}\,\frac{3}{2M^2_{16} r_c^2}\,P_l(E_{2p} - \epsilon, r_c, 2Z(^{16}\mathrm{O}))\,, \quad (6)$$

where $l = 1$ for the 1^- state and the average internal energy of the 'diproton' $\epsilon \sim 0.3$ MeV is estimated from the experimental distribution Fig. 4 in [1]. The usual assumption is to take $\epsilon = 0$ (see for example [16,17]) or $\epsilon = 0.05 - 0.1$ MeV (for example [18,19]) as the energy of the 'virtual state' in two-proton system, but these prescriptions run into methodological problems [20,6]. There is no need to follow these prescriptions if one has an idea what this energy actually is. The use of the 'experimental' diproton energy in Eq. (6) provides an estimated branching ratio $\Gamma_{2p}/\Gamma = (2-10)\times 10^{-4}$ which is in a very good agreement with the simultaneous emission estimate above. Figure 2 shows the ratio Γ_{2p}/Γ for both types of estimates as a function of channel radius r_c.

Discussion. In the estimates above we have made several assumptions. Each of them is likely to give us the *upper* limit for the $2p$ production cross section. We should also note that the source of the theoretical uncertainty in the $2p$ cross section is a variation of the channel radius r_c. The source of experimental uncertainty in the two-proton production cross section is connected with different assumptions about the decay process ('diproton' decay or 'democratic' decay) in the analysis of the data, because of the limited acceptance of the experiment.

The estimates for Γ_{2p}/Γ ratio are consistent with theoretical estimates in [1]. We deduce from Eq. (3) an estimated two-proton production cross section through the 1^- resonance of $0.03-0.2$ mb, much smaller[1] than the measured value $1.5-4.0$ mb reported in [1].

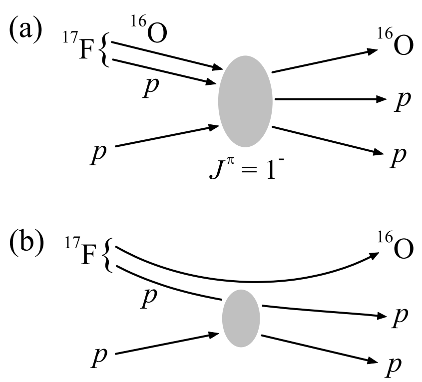

FIG. 3. Schematic presentation of (a) emission of two protons via the decay of resonance in ^{18}Ne, and (b) dominating mechanism of ^{17}F breakup on protons.

There are two possible explanations of the large two-proton production cross section seen in the experiment of [1].

(i) According to the level scheme in the isobaric ^{18}O nucleus, and to the experimental evidence from [21,1], the 2^- and 3^- states are located only slightly higher than the 1^- state. Two-proton contributions from the 3^- state should be negligible, as $l_1 = 1$ and $l_2 = 2$ for the simultaneous emission model Eq. (5), or $l = 3$ for 'diproton' emission Eq. (6). The 'diproton' emission from a 2^- state is parity forbidden as has been mentioned in [1], but simultaneous two-proton emission is allowed with the same quantum numbers $l_1 = 0$ and $l_2 = 1$ as from the 1^- state, with a width comparable with the 'diproton' mechanism (see Fig. 2, dashed line). Using Eqs. (3) and (5) we obtain the value of $\sigma_{2p}^{2^-} \sim 0.1-0.4$ mb. This value would decrease significantly the difference between measured and estimated two-proton production cross sections.

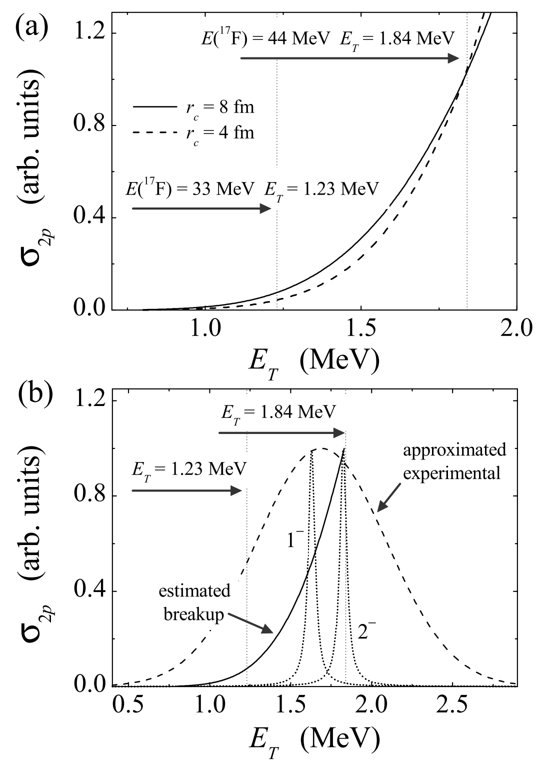

FIG. 4. Qualitative comparison of different possible contributions to the two-proton events. (a) Shows the estimated contributions of possible breakup events in experiments at 33 and 44 MeV beam energies (for different channel radii). Fig. (b) compares the expected shape of the strength functions for breakup events (solid curve is the same as in upper panel), resonance events (from 1^- and 2^- states; dotted curve), and the experimental distribution approximated by a gaussian (dashed curve).

(ii) The other possibility is that most of the two-proton events are actually coming from the breakup of ^{17}F on protons, rather than decay of resonances in ^{18}Ne. Figure 3 schematically outlines the difference between the two processes. It is difficult to estimate the breakup process consistently, as it can involve the complicated interplay of two-body and three-body dynamics. What is important here is that this contribution is not limited by the form of Eq. (3) which applies only for $2p$ production via a resonance.

The energy dependence of the two-proton breakup channel can be roughly estimated by the formula for simultaneous two-proton emission, Eq. (5), as both protons have to penetrate through the Coulomb barrier. However, the channel radius no longer has a well defined meaning, although it is certainly expected to be larger than the values used in estimates for the decay of a compound state. Imagine for the

[1] The branching ratio only gives the experimental cross section if it multiplies a cross section of 3660 mb [1, in note 16] for $1p$ resonance production from Eq. (3).

moment that there is no resonance contribution to the two-proton production at all. The estimated energy dependence of the breakup cross section is shown in Fig. 4a. In the type of experiment described in [1], all beam energies below maximal are present with comparable probabilities because of the thick target used. The estimated ratio of breakup events observed in experiments with 44 MeV and with 33 MeV beams is 20–40 depending on channel radius. This is given by the ratio of integrals of the intensity shown in Fig. 4a up to $E_R = 1.84$ MeV and $E_R = 1.23$ MeV respectively. The main contribution of two-proton events from inelastic breakup comes from the maximal energies available in the experiment. In Fig. 4b this contribution is qualitatively compared with the expected contribution from 1^-, 2^- states and the distribution of actually observed events, which is broad due to the energy resolution being low in the experiment. In our view all the above mechanisms could contribute to the experimental cross sections.

The ratio of the two-proton cross section for the $E_{lab}(^{17}\mathrm{F}) = 33$ MeV measurement compared to the $E_{lab}(^{17}\mathrm{F}) = 44$ MeV measurement could be possible evidence for identification of decays via the 1^- resonance, and the experiment [1] sees a 7–10 fold suppression at the lower energy. However, we have to be careful that the growth of direct breakup does not dominate any resonance contributions. No resonant $2p$ contribution is expected in the 33 MeV measurement. The estimates of Fig. 4 shows that if the number of two-proton events in 33 MeV measurement is only 10 times lower than in 44 MeV measurement, then extrapolation of the intensity of breakup to higher beam energy gives more than enough $2p$ events to explain the whole $2p$ intensity in 44 MeV measurement. This indicates that further experimental evidence will be need to discriminate between direct breakup and resonant decay.

Conclusion. We have shown that it is likely that the two-proton decay of the 1^- state is sufficient to explain only a small fraction of the $2p$ events reported in Ref. [1]. It is plausible that the balance of $2p$ events is connected either with (i) excitation of a 2^- state located a little higher than the 1^- or/and with (ii) the nonresonant breakup of ^{17}F on protons. Identification of the inelastic breakup channel $^{17}\mathrm{F}(1/2^+) + p$ for the states involved in the two-proton emission is also desirable for a refined interpretation of the data. A complete kinematics experiment would be the most useful in the study of $2p$ emission from ^{18}Ne. It would allow the energy of the decaying states in ^{18}Ne to be fixed, and would thus make interpretation of the the experiment clearer.

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[1] J. Gómez del Campo, *et al.*, Phys. Rev. Lett. **86**, 43 (2001).
[2] V. I. Goldansky, Nucl. Phys. **19**, 482 (1960).
[3] O. V. Bochkarev, *et al.*, Pisma Zh. Eksp. Teor. Fiz. **40**, 204 (1984) [JETP Lett. (USSR) **40**, 969 (1984)].
[4] B. V. Danilin, Yad. Fiz. **46**, 427 (1987) [Sov. J. Nucl. Phys. **46**, 225 (1987)].
[5] O. V. Bochkarev, *et al.*, Yad. Fiz. **55**, 1729 (1992) [Sov. J. Nucl. Phys. **55**, 955 (1992)].
[6] L. V. Grigorenko, I. G. Mukha, R. C. Johnson, I. J. Thompson, and M. V. Zhukov, Phys. Rev. C **64**, 054002 (2001).
[7] G. J. KeKelis *et al.*, Phys. Rev. C **17**, 1929 (1978).
[8] C. J. Woodward, R. E. Tribble, and D. M. Tanner, Phys. Rev. C **27**, 27 (1983).
[9] L. V. Grigorenko, I. G. Mukha, I. J. Thompson, and M. V. Zhukov, Phys. Rev. Lett. in print.
[10] C. R. Bain *et al.*, Phys. Lett. **B373**, 35 (1996).
[11] R. J. N. Phillips, Nucl. Phys. **53**, 650(1964).
[12] I. G. Mukha *et al.*, Nucl. Phys. **A630**, 394c (1998).
[13] L. V. Grigorenko, R. C. Johnson, I. G. Mukha, I. J. Thompson, and M. V. Zhukov, Phys. Rev. Lett. **85**, 22 (2000).
[14] G. R. Satchler, *Introduction to nuclear reactions.* Macmillan, London, 1980, pp223-238.
[15] A. Lane and R. Thomas, Rev. Mod. Phys. 30, 257 (1958).
[16] B. A. Brown, Phys. Rev. C **43**, R1513 (1991); **44**, 924(E) (1991).
[17] W. Nazarewicz *et al.*, Phys. Rev. C **53**, 740 (1996).
[18] V. I. Goldansky, Phys. Lett. **14**, 233 (1965).
[19] J. Jänecke, Nucl. Phys. **61**, 326 (1965).
[20] F. C. Barker, Phys. Rev. C **63**, 047303 (2001)
[21] K. I. Hahn *et al.*, Phys. Rev. C **52**, 1999 (1996).